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RESEARCH ARTICLE

JUSTIFICATION OF DESIGN SOLUTIONS FOR THE CONSTRUCTION OF A TRANSPORT INTERCHANGE UNDER DENSE URBAN DEVELOPMENT CONDITIONS: THE CASE OF SHYMKENT CITY

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Abstract. *Rapid urbanization and continuous growth in motorization require comprehensive approaches to selecting transport interchange design solutions in densely developed urban areas, where traffic, spatial, and economic constraints must be considered simultaneously. The aim of this study is to justify the optimal design solution for a transport interchange at the intersection of Zhibek Zholy and Sairamskaya Streets in Shymkent, Kazakhstan. The research methodology included a review of international experience and regulatory requirements, field traffic surveys, assessment of existing planning and geometric constraints, traffic demand forecasting, and comparative evaluation of alternative engineering solutions. Two interchange configurations were developed and assessed: a two-level scheme with flyovers and turnaround ramps, and a three-level configuration incorporating an intermediate roundabout. The results demonstrate that the first alternative leads to overloading of individual interchange elements, requires additional demolition of surrounding buildings, and involves substantially higher construction costs. In contrast, the second alternative provides sufficient traffic capacity under projected demand, distributes traffic flows more efficiently, minimizes impacts on the surrounding urban environment, and reduces overall construction costs. The study concludes that a compact three-level interchange with an intermediate roundabout represents the most balanced engineering solution for densely built urban areas by effectively integrating transport performance, spatial feasibility, and economic efficiency. The proposed approach can support transport infrastructure planning and decision-making in rapidly developing cities.*

Keywords: *transport interchange, dense urban development, traffic intensity, multi-level intersections, urban road network, transport infrastructure*

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ҒЫЛЫМИ МАҚАЛА

ТЫҒЫЗ ҚАЛАЛЫҚ ҚҰРЫЛЫС ЖАҒДАЙЫНДА КӨЛІК АЙРЫҒЫН САЛУҒА АРНАЛҒАН ЖОБАЛЫҚ ШЕШІМДЕРДІ НЕГІЗДЕУ: ШЫМКЕНТ ҚАЛАСЫ МЫСАЛЫНДА

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Аңдатпа. *Қарқынды урбандалу және автокөлік санының тұрақты өсуі жағдайында тығыз қалалық құрылыс аумақтарында көлік айрықтарының оңтайлы жобалық шешімдерін таңдау көлік, кеңістіктік және экономикалық факторларды кешенді түрде ескеруді талап етеді. Зерттеудің мақсаты – Шымкент қаласындағы Жібек жолы мен Сайрам көшелерінің қиылысында көлік айрығының оңтайлы жобалық шешімін негіздеу. Зерттеу әдістемесі халықаралық тәжірибе мен нормативтік құжаттарды талдауды, көлік ағындарына далалық зерттеулер жүргізуді, қолданыстағы жоспарлау және геометриялық шектеулерді бағалауды, есептік кезеңге арналған көлік қозғалысының қарқындылығын болжауды және баламалы жобалық шешімдерді салыстырмалы бағалауды қамтыды. Зерттеу барысында екі нұсқа қарастырылды: эстакадалар мен кері бұрылыс съездері бар схема және аралық деңгейде айналмалы қозғалысы бар үш деңгейлі схема. Нәтижелер бірінші нұсқаның жекелеген элементтерінің шамадан тыс жүктелетінін, қосымша ғимараттарды бұзуды талап ететінін және құрылыс құнының жоғары екенін көрсетті. Ал екінші нұсқа қажетті өткізу қабілетін қамтамасыз етіп, қозғалыс жүктемесін тиімді бөледі, қолданыстағы құрылысқа әсерді азайтады және құрылыс шығындарын төмендетеді. Зерттеу қорытындысы бойынша аралық деңгейде айналмалы қозғалысы бар ықшам үш деңгейлі көлік айрығы тығыз қалалық құрылыс жағдайында көлік тиімділігі, кеңістіктік іске асырылуы және экономикалық тиімділігі арасындағы оңтайлы тепе-теңдікті қамтамасыз ететін ең тиімді инженерлік шешім болып табылады.*

Түйін сөздер: *көлік айрығы, тығыз қалалық құрылыс, қозғалыс қарқындылығы, көлденеңгейлі қиылыстар, көше-жол желісі, көлік инфрақұрылымы*

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НАУЧНАЯ СТАТЬЯ

ОБОСНОВАНИЕ ПРОЕКТНЫХ РЕШЕНИЙ ПРИ СТРОИТЕЛЬСТВЕ ТРАНСПОРТНОЙ РАЗВЯЗКИ В УСЛОВИЯХ ПЛОТНОЙ ГОРОДСКОЙ ЗАСТРОЙКИ: НА ПРИМЕРЕ ГОРОДА ШЫМКЕНТ

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Аннотация. *В условиях интенсивной урбанизации и роста автомобилизации выбор рациональных проектных решений для транспортных развязок в плотной городской застройке требует комплексного учета транспортных, пространственных и экономических факторов. Целью исследования является обоснование оптимального варианта транспортной развязки на пересечении улиц Жибек Жолы и Сайрамская в городе Шымкент. Методология исследования включала анализ международного опыта и нормативных требований, проведение натурных обследований транспортных потоков, оценку существующих планировочных и геометрических ограничений, прогнозирование интенсивности движения на расчетный период и сравнительную оценку альтернативных проектных решений. Рассмотрены два варианта развязки: схема с эстакадами и разворотными съездами, а также трехуровневая схема с промежуточным кольцевым движением. Результаты показали, что первый вариант приводит к перегрузке отдельных элементов развязки, требует дополнительного сноса зданий и характеризуется более высокой стоимостью строительства. Второй вариант обеспечивает необходимую пропускную способность, снижает нагрузку на отдельные направления движения, минимизирует воздействие на существующую застройку и имеет меньшую ориентировочную стоимость. Сделан вывод, что компактная трехуровневая развязка с внутренним кольцевым движением является наиболее сбалансированным решением для условий плотной городской среды.*

Ключевые слова: *транспортная развязка, плотная городская застройка, интенсивность движения, многоуровневые пересечения, улично-дорожная сеть, транспортная инфраструктура*

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1 INTRODUCTION

Transport interchanges represent essential elements of urban road networks, ensuring increased traffic capacity, reduced delays, and improved road safety [1-4]. Under conditions of rapid urbanization and continuous growth of motorization, the modernization of overloaded intersections has become one of the key challenges of transport infrastructure development, particularly in large cities characterized by dense urban development and limited territorial resources [5-7].

International experience demonstrates that grade-separated interchanges, including cloverleaf, directional, and multi-level configurations, are effective solutions for improving traffic performance and reducing conflict points [8-14]. However, their implementation in densely developed urban areas is often associated with significant engineering and socio-economic challenges, including high construction costs, limited right-of-way, relocation of utility networks, and negative impacts on the surrounding urban environment. These circumstances require comprehensive justification of design solutions at the early planning stages.

Despite the considerable number of studies [9-13] devoted to transport interchanges, most existing research focuses primarily on traffic performance indicators or individual engineering solutions. Spatial constraints, urban-planning factors, and socio-economic impacts are usually considered separately. As a result, there is a lack of integrated approaches capable of combining transport efficiency with the specific requirements of dense urban environments. This issue is particularly relevant for rapidly developing cities of the Republic of Kazakhstan, where increasing motorization and limited opportunities for infrastructure expansion create additional challenges for transport planning.

Therefore, a clear research gap exists in the lack of a comprehensive methodology for selecting transport interchange design solutions that simultaneously integrates technical, spatial, and economic criteria within a unified decision-making framework.

The aim of this study is to justify design solutions for the construction of a transport interchange under conditions of dense urban development based on a systematic multi-criteria approach. To achieve this objective, international experience in interchange design was analyzed, the transport and spatial characteristics of the studied intersection in Shymkent were assessed, alternative design solutions were developed, and a comparative evaluation of the proposed options was performed.

The scientific novelty of the study lies in the integrated justification of transport interchange design solutions through the combination of international experience, assessment of local spatial constraints, and comparative techno-economic analysis of alternative engineering schemes. Unlike conventional approaches focused mainly on traffic capacity, the proposed methodology simultaneously considers transport efficiency, urban-planning limitations, and socio-economic factors.

The practical significance of the research lies in the possibility of applying the obtained results to the design and reconstruction of transport hubs in large cities of Kazakhstan and other rapidly developing urban areas characterized by constrained spatial conditions.

International studies devoted to transport interchanges in dense urban environments can generally be classified into three major research directions.

The first group of studies focuses on the transport efficiency of grade-separated intersections, mainly addressing capacity enhancement, delay reduction, and traffic safety improvement [14;15]. These studies consistently demonstrate the advantages of multi-level solutions over at-grade intersections. However, most of them are based on idealized traffic conditions and primarily evaluate operational indicators without considering spatial limitations and the influence of surrounding urban development. Consequently, their applicability to densely built urban areas remains limited.

The second group of studies investigates urban-planning, environmental, and social aspects associated with transport infrastructure integration [9; 16-18]. These studies emphasize the importance of minimizing visual intrusion, preserving existing buildings, and reducing negative social impacts. Nevertheless, the majority of these works provide mainly qualitative assessments and

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do not propose engineering criteria for selecting optimal interchange configurations. As a result, urban-planning considerations are often analyzed separately from transport performance indicators.

The third research direction is associated with intelligent traffic management systems and innovative intersection concepts [19; 20]. These approaches demonstrate considerable potential for increasing capacity and reducing delays through connected and automated transport technologies. However, most of these concepts are still at the experimental stage and require a high level of technological maturity, which restricts their practical implementation, especially in developing countries.

The results summarized in Table 1 demonstrate that each engineering approach possesses both significant advantages and substantial limitations. Grade-separated interchanges provide high capacity and safety; however, their implementation under dense urban conditions is often constrained by limited space, high construction costs, and adverse impacts on surrounding development. At the same time, studies addressing urban-planning and social aspects rarely provide quantitative criteria for engineering decision-making. This indicates the necessity of balancing transport performance with spatial and economic constraints.

Table 1 - Comparative analysis of international experience in designing transport interchanges under conditions of dense urban development [Authors' material]

№	Analysis criterion	Identified advantages	Identified limitations and problematic aspects	Source
1	Road Network Capacity	A significant increase in capacity through the separation of traffic flows by levels and directions of movement	Limited opportunities for expansion and modernization under constrained existing development conditions	[15; 21]
2	Road Traffic Safety	Reduction in the number of conflict points and accident rates through the elimination of at-grade intersections	Increased requirements for ramp geometry and sight distance, with a higher risk of accidents at merge and diverge areas under conditions of insufficient space	[21; 22]
3	Spatial Constraints	The possibility of redistributing traffic flows without the implementation of signalized control	A shortage of space for accommodating ramps, connectors, and turning elements, and the necessity of integrating structures into the existing development	[16; 21]
4	Economic indicators	Long-term benefits resulting from reduced transport losses and delays	High construction costs, relocation of utility networks, and increased project costs under constrained conditions	[21; 23]
5	Urban planning impact	Improvement of the functional efficiency of transport hubs	Negative impact on the urban environment, visual intrusion, and potential demolition of existing buildings	[16; 17]
6	Social factors	Improvement of traffic conditions and reduction in travel time	Social tension associated with land acquisition and construction activities in residential areas	[16; 18]

The data presented in Table 1 confirm that each group of solutions is associated with both significant advantages and substantial limitations. However, the analysis also shows that most studies consider these factors independently, without providing a unified methodology for balancing transport efficiency with spatial and urban-planning constraints. This limits the applicability of existing approaches in real design practice under conditions of dense urban development.

Table 2 shows that although intelligent and innovative traffic management concepts have considerable potential, their practical implementation remains limited. Conventional grade-separated and combined interchange configurations continue to represent the most technically feasible solutions

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for densely developed urban areas. However, existing studies mainly focus on isolated aspects of transport performance and rarely provide an integrated assessment of traffic efficiency, spatial limitations, construction costs, and urban-planning impacts.

Table 2 - Comparison of contemporary approaches to traffic organization at overloaded intersections [Authors' material]

№	Solution	Primary effect	Constraints	Source
1	Grade-separated transport interchanges (classical, diamond, and their modifications)	A substantial reduction in conflict points and accident rates, along with a significant increase in traffic capacity	High construction costs, implementation complexity, and the risk of forming "bottlenecks" at traffic weaving sections	[22; 24]
2	Roundabouts and combined ("smart") traffic schemes	Reduction of traffic conflicts and simplification of turning movement organization	A compromise between safety and efficiency, with a potential increase in delays and queue lengths under high traffic demand	[25; 26]
3	Intelligent slot-based intersections (conceptual solutions)	Potential twofold increase in capacity and a sharp reduction in delays	They require a high level of vehicle and infrastructure automation and have not yet been implemented in practice	[19]

A comparative analysis of the available literature indicates that existing studies are characterized by a fragmented approach. Traffic efficiency, urban-planning constraints, economic feasibility, and social factors are usually investigated independently rather than within a unified decision-making framework. Furthermore, most studies are based on generalized or idealized conditions and provide limited evidence from real cases in rapidly developing cities with constrained territorial resources.

Another important limitation concerns the lack of comparative assessments of alternative interchange configurations under actual urban conditions. Existing research predominantly evaluates individual engineering solutions without considering the trade-offs between transport performance, land use constraints, construction costs, and impacts on surrounding development. Consequently, the practical applicability of many proposed solutions remains limited.

Therefore, a clear research gap exists in the absence of a comprehensive methodological framework that integrates traffic, spatial, urban-planning, and economic criteria for selecting transport interchange solutions under conditions of dense urban development. Furthermore, limited attention has been given to empirical case studies from rapidly developing cities in the Republic of Kazakhstan, where increasing motorization and constrained opportunities for infrastructure expansion necessitate balanced and context-sensitive engineering solutions.

This study aims to address this gap by proposing a multi-criteria approach to the justification of transport interchange design solutions based on real traffic data, spatial constraints, and comparative evaluation of alternative engineering schemes.

2 MATERIALS AND METHODS

2.1 Study area and object of research

The study area is located within the established urban development of Shymkent and is characterized by a high density of heterogeneous land uses, including residential, public–business, and commercial development. The road network is formed by major arterial streets providing connections between key urban districts.

The object of the study is the intersection of Zhibek Zholy and Sairamskaya streets, which currently operates as an at-grade intersection and represents one of the most heavily loaded transport

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nodes in the study area [27;28]. The intersection is characterized by high traffic intensity, limited right-of-way, and the presence of surrounding development and engineering utilities, which significantly constrain possible design solutions. At the time of the study, the intersection was characterized by limited capacity and recurrent traffic congestion during peak hours. The existing traffic organization scheme does not provide the required level of service and does not meet projected traffic demand. The spatial layout of the intersecting streets, adjacent development, and elements of the road network are shown in figure 1.

Figure 1 - Layout of the arterial street intersection in Shymkent (prior to construction of the transport interchange) [Authors' material]

Assessment of the existing traffic intensity at the studied intersection was carried out based on field surveys of traffic flows. Measurements were conducted on typical working days during morning and evening peak hours, taking into account daily and hourly traffic variability. Traffic intensity was recorded for the main movement directions with classification of vehicles by category (passenger cars, freight vehicles, and public transport). The obtained data were used to determine the degree of intersection loading, identify conflict points, and assess the level of service.

2.2 Research methodology

The research methodology is based on a consistent multi-stage approach that integrates field data collection, analytical assessment, and comparative evaluation of design solutions (figure 2).

At the first stage (figure 2), an analysis of regulatory and technical documentation of the Republic of Kazakhstan and international scientific studies was conducted. This stage made it possible to identify the main requirements for the design of transport interchanges and the limitations associated with dense urban development. At the second stage (figure 2), field observations of traffic flows were carried out at the studied intersection. Traffic counts were conducted during morning and evening peak periods on working days. Vehicle flows were classified by type (passenger cars, buses, freight vehicles), and traffic intensity was recorded for the main movement directions. At third stage (figure 2), the existing planning structure of the intersection was analyzed, including road geometry, surrounding development, and engineering infrastructure. Constraints related to limited space and urban environment were identified. At fourth stage (figure 2), Future traffic demand was estimated using a growth model based on an annual growth coefficient. This made it possible to assess the projected load on the intersection and justify the necessity of grade separation. Next stage (figure 2) based on the collected data and identified constraints, alternative transport interchange solutions were developed, considering both traffic requirements and spatial limitations. At the final stage (figure 2),

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the developed design options were evaluated using a set of criteria, including traffic capacity, spatial feasibility, and economic indicators, which allowed the selection of the most rational solution.

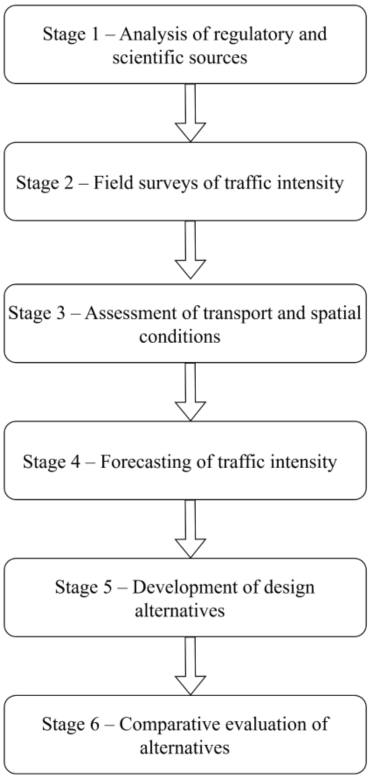

Figure 2 - Research methodology algorithm [Authors' material]

At the same time, an analysis of international experience in the design of transport interchanges was carried out, aimed at identifying the most effective engineering and planning solutions applied under conditions of dense urban development, as well as at assessing the possibilities of their adaptation to local conditions.

To obtain objective baseline data, field surveys of traffic flow intensity were conducted at the studied intersection, including recording traffic volumes along the main directions at different times of day. The obtained results were used to assess the degree of intersection loading and to determine the necessity of transitioning to a grade-separated traffic organization.

Based on the collected data, a comparative analysis of alternative transport interchange design solutions was performed, in which various traffic organization schemes were examined with due consideration of the spatial constraints of the site. The final stage of the methodological framework involved evaluation of the design solutions according to a set of technical, functional, and economic criteria, which made it possible to substantiate the most rational transport interchange option for implementation under conditions of dense urban development.

2.3 Research algorithm

The overall research algorithm is presented as a sequence of interrelated stages:

1. Analysis of international experience and regulatory requirements
2. Field surveys and collection of traffic data
3. Assessment of existing transport and spatial conditions
4. Forecasting of traffic intensity
5. Development of alternative design solutions
6. Comparative evaluation and selection of the optimal option

The proposed algorithm ensures a systematic approach to the justification of transport

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interchange design solutions under conditions of dense urban development.

3 RESULTS AND DISCUSSION

The results of the conducted surveys showed that during peak hours the total traffic intensity through the intersection exceeds the calculated capacity of the junction. This leads to queue formation and a reduction in average travel speed. The greatest delays are observed along the directions of the main traffic flows, which confirms the necessity of transitioning to a grade-separated traffic organization solution. Data on traffic intensity prior to the construction of the transport interchange are presented in figure 3 and were subsequently used to substantiate the proposed design solutions.

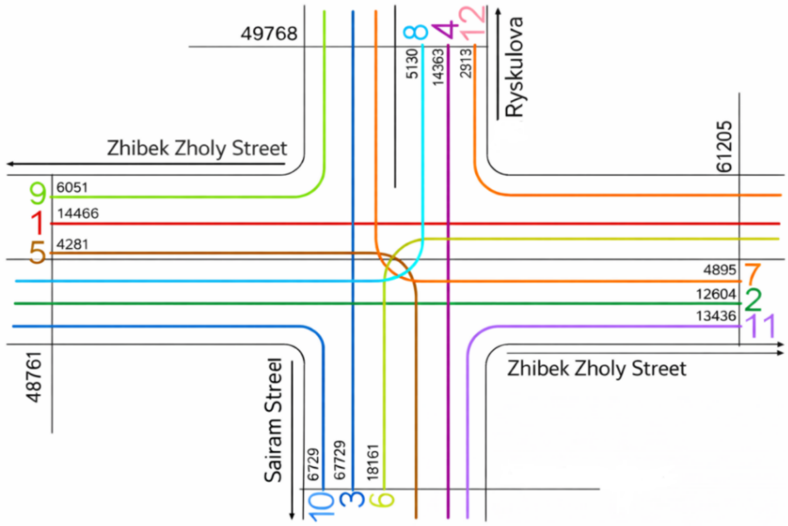

Figure 3 - Traffic intensity at the intersection prior to construction of the transport interchange (traffic intensity diagram for 2025, vehicles/day) [Authors' material]

Based on the field survey data, an assessment of future traffic demand was carried out. The calculation of projected (forecast) traffic intensity was performed for a design horizon of 12 years using an annual traffic growth factor of 1.04, which corresponds to the forecasted rate of motorization growth in large cities of the Republic of Kazakhstan. The results of the calculations of current and projected traffic intensity for the main movement directions are presented in Table 1. Analysis of the obtained data showed that, at projected traffic volumes, at-grade operation does not provide the required level of capacity. This confirms the necessity of implementing a grade-separated intersection with separation of traffic flows across different levels.

To quantitatively assess the traffic load at the studied intersection, field surveys of traffic intensity along the main movement directions were conducted. Vehicle counts were performed with differentiation by travel direction and vehicle type during representative periods of the day. The survey results, reflecting daily and design hourly traffic intensities, are presented in Table 3.

Table 3 - Traffic flow intensity at the intersection of Zhibek Zholy and Sairamskaya streets in Shymkent (daily and hourly values) [Authors' material]

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Conversion factors	Years	Cars	Buses with an average capacity	Buses with a large capacity	Small trucks with a carrying capacity of up to 2 tons	Medium trucks with a carrying capacity of 2 to 5 m	Two-axle trucks with a load capacity of up to 10 m	Three-axle trucks with a carrying capacity of up to 10 tons	In all
Main roads									
Sairamskaya	2021	25173	3937	3936	8789	12404	4857	5399	67616
	2022	26180	4094	4093	9141	12900	5051	5615	70321
	2024	28316	4429	4427	9886	13953	5463	6073	76059
	2042	57363	8972	8969	20028	28266	11068	12303	154081
Calculation of the reduced intensity to the A2 load									
Sairamskaya	2024	28316	4429	4427	9886	13953	5463	6073	76058,804
	Npr	0	49	1018	0	837	2513	1032	14928
Conversion factors		1	3	5	2	2	3	3	
Brought to a passenger car for 2042g		57363	26915	44846	30042	56532	27670	36909	305169

Analysis of the data presented in Table 3 indicates that the intersection of Zhibek Zholy and Sairamskaya streets operates under conditions of high traffic demand. On certain approaches and movement directions, hourly traffic volumes are recorded that approach or exceed the permissible limits for a single traffic lane. The main arterial traffic directions are the most heavily loaded, which leads to the formation of persistent traffic congestion during peak hours and a reduction in average travel speed.

The obtained traffic intensity values confirm that the existing at-grade traffic organization scheme does not provide the required level of capacity and does not correspond to projected operating conditions. These results served as the baseline for the development and comparative analysis of alternative grade-separated transport interchange options.

Based on the analysis of traffic flows, existing spatial constraints, and the requirements of regulatory documents [29;30], alternative design options for the transport interchange were developed. The primary objective of the design solutions was to ensure the required traffic capacity while minimizing impacts on surrounding development and existing infrastructure. Within the scope of the study, two alternative interchange configurations were considered (schematic layouts are shown in Figures 3 and 4). To substantiate the selection of the structural solution, a comparative analysis of the proposed options was carried out. The key technical and functional indicators of these options are summarized in Table 4.

Option 1 (figure 4) of the transport interchange provides for uninterrupted (non-stop) traffic in both directions along Zhibek Zholy and Sairamskaya streets. Left-turn movements are proposed to be accommodated by two separate overpasses (flyovers) located along Zhibek Zholy on the right and left sides of the intersection. Under this design, traffic flow along Zhibek Zholy would be constrained in the outer right lanes in both directions, since vehicles making a left turn from Zhibek Zholy must cross the intersection with Sairamskaya via an overpass, then proceed to a dedicated turning area, perform a U-turn, and finally merge into the outer right lane. Similarly, vehicles turning left from Sairamskaya are required to first execute a right turn, travel along the outer right lane to a turning area, perform a U-turn, and then enter the outer right lane in the opposite direction. This scheme creates an additional load on the outer right traffic lanes. In addition, construction of the turning area would require further demolition of existing buildings. The calculated traffic load on the outer right lane in Option 1 is approximately 12,891 vehicles/day (2,153 vehicles/hour per lane), which exceeds the maximum allowable intensity of about 2,000 vehicles/hour per lane. Moreover, traffic intensity on the two-level turning ramp reaches 17,786 vehicles/day (2,970 vehicles/hour per lane), which is

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significantly higher than the permissible limit of 2,000 vehicles/hour. Thus, traffic operation at the interchange under Option 1 would be substantially hindered due to overloading of individual interchange elements.

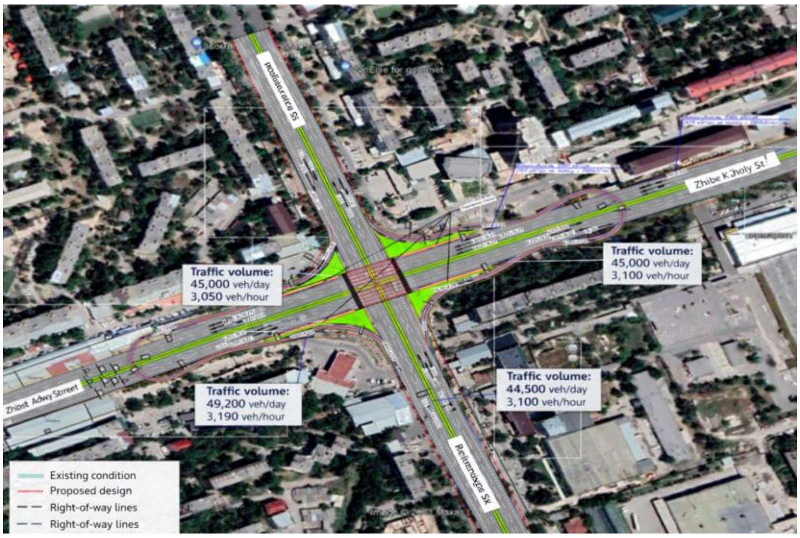

Figure 4 - Layout of the proposed Option 1 transport interchange at the intersection of Zhibek Zholy and Sairamskaya streets [Authors' material]

Option 2 (figure 5) of the transport interchange also provides uninterrupted traffic along the main directions of Zhibek Zholy and Sairamskaya streets, but is implemented as a three-level configuration: Zhibek Zholy runs at the upper level (overpass), Sairamskaya runs at the lower (underground) level, and a roundabout is arranged between the upper and lower levels to distribute turning traffic flows. This scheme eliminates vehicle accumulation and stopping at the intersection, as all left-turn movements are carried out via circulation on a compact roundabout, which is not expected to be overloaded. The design diameter of the roundabout is approximately 40 m, which minimizes the occupied area and allows the interchange to be integrated into constrained urban development conditions [31;32]. Traffic intensity on the roundabout is relatively low and amounts to about 27,197 vehicles/day (1,514 vehicles/hour per lane), which is below the permissible limit of 2,000 vehicles/hour. Thus, the capacity of the roundabout interchange will be sufficient with an adequate margin, and vehicle accumulation on the roundabout is not expected.

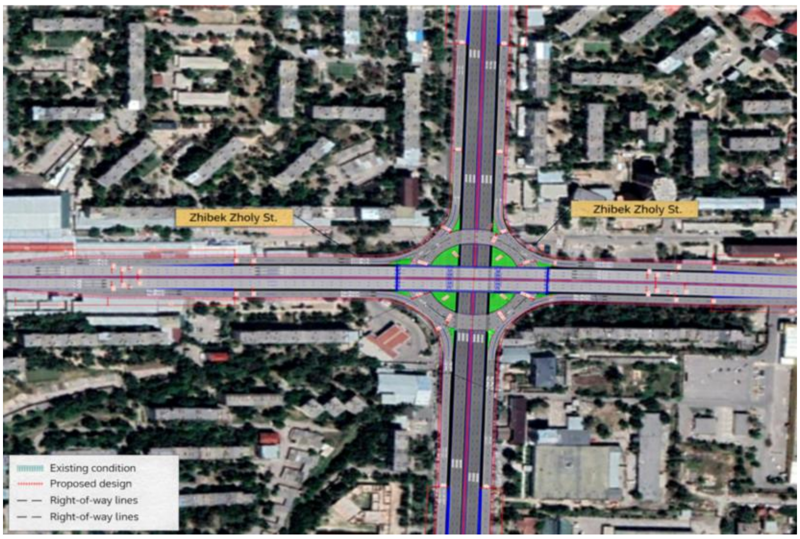

Figure 5 - Layout of the proposed Option 2 transport interchange (with an internal roundabout) at the studied junction [Authors' material]

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For a clear comparison of the key parameters of the developed solutions, a comparative table of the main characteristics of the two options is presented below.

Table 4 - Comparative characteristics of the transport interchange options [Authors' material]

№	Indicator	Option 1 (overpasses + turnaround ramps)	Option 2 (overpass + tunnel + roundabout)
1	Level configuration	Two-level configuration (uninterrupted movement along the main directions; left-turn movements accommodated via separate overpasses and a turnaround facility).	Three-level configuration (upper-level through movement along Zhibek Zholy, lower-level through movement along Sairamskaya, with an intermediate roundabout accommodating all turning movements).
2	Left-turn organization	Left turns are executed via an initial right turn followed by a U-turn on separate ramps (direct left turns at the intersection are not provided). Left turns are executed via an initial right turn followed by a U-turn on separate ramps (direct left turns at the intersection are not provided).	Left-turn traffic flows circulate through the central roundabout, without the need for additional U-turns at a distance.
3	Requirement for demolition of buildings	Demolition of buildings is required to accommodate the turnaround ramps (expansion of the right-of-way).	There is no need to demolish existing buildings (compact layout within the existing boundaries).
4	Maximum load on an individual element	Right-turn lanes are overloaded, reaching up to approximately 2,153 vehicles/hour per lane (exceeding the allowable capacity).	The load on the roundabout is approximately 1,514 vehicles per hour per lane (within the permissible capacity).
5	Estimated cost	Approximately KZT 32 billion (high construction cost).	Approximately KZT 20 billion (significantly lower than the cost of Option 1).
6	Efficiency assessment	Low efficiency (risk of localized overloading, impediments to traffic flow, and negative impacts on the surrounding development).	High efficiency (the required capacity is ensured with minimal impact on the urban environment).

Considering the projected traffic demand, constrained spatial conditions, and techno-economic indicators, the most rational solution for the given conditions is the transport interchange option that achieves a balance between traffic capacity and urban planning constraints [31]. The selected design solution (the option with a roundabout at the intermediate level) makes it possible to significantly improve the operational efficiency of the junction and creates a reserve for the further development of the area's transport infrastructure.

Analysis of international experience [15; 24-26] has shown that, despite the evident advantages of grade-separated transport interchanges, their implementation under conditions of dense urban development is associated with a number of challenges, including high construction costs, the need for land acquisition and demolition of existing buildings, as well as adverse impacts on the environment and the urban fabric. Therefore, careful elaboration of design solutions at the early planning stages is particularly important to minimize these risks. The case of the intersection of Zhibek Zholy and Sairamskaya streets illustrates a typical situation in which prospective growth in traffic demand necessitates a transition from an at-grade traffic scheme to a grade-separated one. An increase in traffic intensity within the existing configuration inevitably leads to congestion and reduced traffic speeds, which substantiates the rationale for selecting a grade-separated interchange solution.

A comparison of the two developed interchange options revealed substantial differences in their technical and operational characteristics. The option incorporating a roundabout at the intermediate

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level proved to be optimal in terms of capacity and with respect to minimizing impacts on the surrounding development. The comparative analysis demonstrated that the second option provides the required capacity under projected traffic volumes and is characterized by a lower negative impact on existing buildings and infrastructure. Its estimated cost (approximately KZT 20 billion) is significantly lower than that of the first option (approximately KZT 32 billion), which enhances its economic feasibility. In addition, socio-urban considerations played an important role: the second scheme minimizes intervention in the residential environment and avoids the need for demolition of existing buildings. This contributes to a more favorable perception of the project by local residents and reduces potential social conflicts during implementation.

Thus, the comprehensive substantiation of the design solution confirmed that the second option achieves a balance between the need to increase the capacity of the transport node and compliance with urban planning constraints, while minimizing financial and social costs.

The obtained results were compared with findings from previous studies on the design and performance of transport interchanges in dense urban environments.

Consistent with the results reported by Wang [33] and Naser [15], the present study confirms that grade-separated interchanges significantly improve traffic capacity and reduce delays compared to at-grade intersections. However, unlike these studies, which are primarily based on idealized or less constrained conditions, the current research demonstrates that the effectiveness of classical multi-level solutions may be substantially reduced under conditions of limited urban space due to the formation of localized bottlenecks and excessive load on individual elements of the interchange.

The findings also support the conclusions of Conticelli [9] and Ivashenko [17], who emphasize the importance of integrating transport infrastructure into the urban environment. In this study, it is shown that design solutions requiring demolition of existing buildings and expansion of the right-of-way are less preferable, even if they provide sufficient traffic capacity.

At the same time, in contrast to studies focused on intelligent or experimental traffic management systems [19;20], the present research demonstrates that, under real conditions of developing cities such as Shymkent, practical and implementable engineering solutions remain more relevant than conceptual models.

A key contribution of this study is the demonstration that the optimal design solution should be selected not only based on traffic performance indicators but also by taking into account spatial constraints, economic feasibility, and urban-planning impact. This confirms the need for a multi-criteria approach, which is insufficiently addressed in existing research.

Thus, the results of the study expand existing knowledge by providing an applied framework for selecting transport interchange solutions under conditions of dense urban development, based on real data and integrated evaluation criteria.

4 CONCLUSIONS

The study presents a comprehensive justification of transport interchange design solutions under conditions of dense urban development, based on an integrated and multi-criteria approach.

The main scientific results of the study are as follows:

1. It is established that under conditions of limited urban space, conventional multi-level interchange solutions may lose their effectiveness due to the formation of localized bottlenecks and excessive load on individual elements of the interchange.
2. A methodological approach for the selection of transport interchange design solutions is developed, which integrates traffic performance indicators with spatial constraints, economic feasibility, and urban-planning factors.
3. Based on field data and forecasting of traffic intensity, it is demonstrated that the existing at-grade intersection does not meet current and projected transport demand, which justifies the necessity of grade separation.

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4. A comparative analysis of two design alternatives shows that a three-level interchange with an intermediate roundabout provides the optimal balance between capacity, spatial feasibility, and cost efficiency.

5. It is demonstrated that compact design solutions that minimize the impact on existing development are more effective under conditions of dense urban environments than traditional large-scale interchange configurations.

The obtained results may serve as a practical basis for the planning and design of transport infrastructure in rapidly developing cities and contribute to more effective decision-making in the development of transport interchanges under conditions of constrained urban development.

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